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ROCKETDYNE

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CANOGA PARK, CALIFORNIA

R-2452-5

(UNCLASSIFIED TITLE) 38

RESEARCH ON THE HAZARD CLASSIFICATION OF NEW LIQUID ROCKET PROPELLANTS

QUARTERLY PROGRESS REPORT FOR PERIOD ENDING 30 APRIL 1961

ROCKETDYNE
A DIVISION OF NORTH AMERICAN AVIATION, INC.
6633 CANOGA AVENUE
CANOGA PARK, CALIFORNIA

Contract AF33(616)-6939

G.O. 5811

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REVISIONS

DATE 30 April 1961

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FOREWORD

This quarterly progress report covers work performed on Contract AF33(616)-6939, PN 3148, TN 30196 for FTRPL, U.S. Air Force, Edwards AFB, California.

ABSTRACT

This report describes the progress during the fourth quarter of a research program to determine the hazards of (1) pentaborane, (2) chlorine trifluoride, (3) nitrogen tetroxide, and (4) hydrazine, and associated air-contamination phenomena. The application of this information is in the basic design of storable propellant handling and storage areas where practical safety criteria are now lacking. This report includes quantitative results of fifty-seven small-scale spill tests to supplement the visual results which had been reported in the previous progress report. Also included are additional results from above-ground spills made with the Titan II propellants.

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INTRODUCTION

The emphasis being placed on high-energy propellants has made it imperative that additional data concerning hazards associated with these chemicals be collected to develop handling and storage criteria and establish practical safety procedures.

Performance of these studies and the development of data is requested on Contract AF33(616)-6939. Principal objectives of this program are the determination of safety, medical, and design criteria for systems involving the use of:

1. Nitrogen tetroxide
2. Pentaborane
3. Chlorine trifluoride
4. Hydrazine

An addendum to the above contract requested that additional work be performed with systems utilizing a 50-50 by weight mixture of hydrazine-UDMH and nitrogen tetroxide. This program, conducted for AFBMD, was designed to examine the blast and toxic hazards of spills in large missile silos.

SUMMARY

The large-scale spill tests of Phase III are expected to resume 23 May 1961. Toxicity-monitoring equipment will be available by 1 June 1961 for recording hydrazine and nitrogen tetroxide concentrations on the spills of these propellants.

The design criteria Engineering Design Manual has been completed and review copies are presently being distributed. The Propellant Handling Manual is in rough draft form. After editing and typing, review copies of this report will be distributed.

Quantitative results from 57 small-scale tests are presented to supplement the preliminary results from visual observations previously reported. The spills of chlorine trifluoride, nitrogen tetroxide, hydrazine, and pentaborane were made singly and in pairs, on various surfaces under different ambient conditions. The propellant combinations were tested with both propellants spilled simultaneously, and with one propellant leading the other propellant. Results from all combination spills were recorded by direct observation and color motion pictures; microphone transducers and sound tape were used to record overpressures that occurred during the spills.

Chlorine trifluoride reacted with all surfaces (except the concrete), causing either ignition or weak audible reports; spills of this propellant caused a considerable release of toxic vapors. Spills of pentaborane, on various surfaces, resulted in spontaneous ignition with air under some of the conditions tested. On all surfaces except water, the propellant ignited above ambient temperatures of 70 F. On dirt and asphalt surfaces, reaction between the surface and fuel ignited the propellant below this temperature.

Spills of nitrogen tetroxide with chlorine trifluoride failed to show any indication of reactions under any of the conditions tested. Hydrazine ignited instantaneously with chlorine trifluoride under all test conditions. Some of the tests resulted in a series of very slight overpressures which were compared to equivalent overpressures originating from smaller amounts of TNT. The largest TNT equivalent for this liquid combination was 0.0045 percent. From the motion pictures and the overpressure measurements during these tests, overpressures were traced to reactions between hydrazine vapors and air.

Spills of pentaborane and chlorine trifluoride resulted in hypergolic ignition and intense fireballs. Weak overpressures of less than 0.0003 percent TNT equivalent were recorded on six of the twelve combination spills. Reactions that initiated the shock wave were thought to be reactions of free hydrogen, generated by the pyrolysis of pentaborane and air.

Results from spills of hydrazine and nitrogen tetroxide were very similar to those of the Titan II propellants previously reported. However, the average TNT equivalents from these spills were slightly higher than those recorded for the Titan II tests. The maximum value of overpressures recorded was equal to a TNT equivalent of 0.75 percent. These overpressures, as with the Titan II spills, originated from vapor-phase detonations of hydrazine-air mixtures a few feet above the surface.

The highest overpressure amplitudes that were recorded during the test series were caused by spills of hydrazine and pentaborane on concrete, dirt, and asphalt. Overpressures occurred as a single shock wave with reflections and were originated at times varying from slightly after ignition to the start of the post-test purge. A majority of shock waves that resulted from the tests had not "shocked up" by the time the wave reached the overpressure transducers located at 10 feet. The largest overpressure was recorded at a point 15 feet from the origin and was 3.15 percent equivalent of TNT. Initiation of the shock wave in each test appeared to be a result of a hydrogen/air explosion in which the hydrogen was generated by bipropellant reaction and, under some conditions, was confined with air.

Inquiries concerning the characteristics of formation of the ball of fire (fireball) on the spill reactions aboveground in the tray have prompted additional discussion of the above-ground Titan II model missile studies. On these tests, 200 lb of nitrogen tetroxide and 100 lb of (50-50) hydrazine-UDMH were spilled from tanks that were placed in a test-stand structure with the oxidizer tank positioned above the fuel. Blast measurements and photographic coverage were taken. The radius of the fireball was estimated by comparing its size to the 20 x 20 ft spill tray as shown in the high-speed motion picture frames. The ball of fire reached a maximum radius of approximately 32 feet within 1.5 seconds after rupture on the simultaneous spill, compared to 32 feet radius in 1.8 seconds on the oxidizer-lead spill. Increase in fireball size was noticeably affected by overpressure pulsations that occurred at the center of the ball of fire.

DISCUSSION

LARGE-SCALE HAZARD DETERMINATION TESTS

The large-scale spill tests with biological studies (Phase III of the basic program) are expected to resume 23 May 1961. Presently, 11 tests are scheduled; listed below are the propellant quantities and measurements that will be made on each test of Phase III. Toxicity-monitoring equipment will be available by 1 June 1961 for recording hydrazine and nitrogen tetroxide concentrations on tests 7 through 11. Only limited monitoring of chlorine trifluoride and pentaborane concentrations will be attempted since this detection equipment has not completed laboratory tests and will have but limited field test trials before use.

*1. 500 lb (32.7 gal) CTF; 500 lb (59.5 gal) HZ
2. 750 lb (49 gal) CTF
*3. 750 lb (49 gal) CTF (with water deluge)
4. 100 lb (18.9 gal) Pb; 100 lb (11.9 gal) HZ
5. 100 lb (18.9 gal) Pb
**6. 100 lb (18.9 gal) Pb (external heating)
7. 835 lb (99.5 gal) HZ
*8. 1500 lb (124 gal) NTO; 500 lb (67.5 gal) UDMH-HZ (50-50)
*9. 1500 lb (124 gal) NTO; 500 lb (67.5 gal) UDMH-HZ (50-50)
10. 128 lb (15 gal) HZ (external heating, 90-percent ullage)
**11. 1135 lb (135 gal) HZ (external heating, 10-percent ullage)

* Temperatures and size of ball of fire.

** Temperature and pressure measurements inside tank.

Blast measurements will be made on all tests except tests 2, 6, and 11; other measurements are indicated by asterisk. Biological studies will be performed on tests 2, 3, 7, and 8.

PHASE I

The design criteria Engineering Design Manual has been completed and review copies of this manual are presently being distributed. Release of these manuals for final publication and initial distribution is pending incorporation of changes from comments received on the review copies.

The Propellant Handling and Safety Manual, which discusses each propellant separately in four sections, is in rough draft form. After editing and typing, review copies of this report will be distributed.

Copies of these manuals may be obtained through FTRPL, Edwards AFB, California.

PHASE II: SMALL-SCALE HAZARD DETERMINATION TESTS

Quantitative results from the small-scale tests, the data of which were being reduced and consequently not reported in Rocketdyne Report R-2452-4, are included to supplement the preliminary results from visual observations previously reported. The spill test series was designed to determine the reaction characteristics of pentaborane, hydrazine, nitrogen tetroxide, and chlorine trifluoride when spilled both singly and together on the following surfaces:

1. Dry concrete
2. Dirt
3. Wood

4. Asphalt

5. Painted carbon steel

6. Wet concrete (water covered)

The tests were made using simultaneous propellant mixing, and with one propellant leading or lagging the other propellant.

Test Equipment

The spill system utilized for these tests (as described in R-2452-2) consists of four 1.5-gallon tanks with associated control valves mounted to a facility panel (Fig. 1). Each tank system is designed specifically for the propellant to be handled.

Propellants were spilled in a 4 ft x 4 ft x 1/2 ft-deep concrete tray (Fig. 2) specially constructed for the spill program. A drain opening into the main laboratory drain is used to wash out residual, unburned propellant, and combustion products. The four propellant outlet lines extend from the main valves to within a foot of the spill surface and impinge in a radius of 2 inches. Water is supplied to the pit by means of a de-ionized water line terminating in a spray nozzle 5 feet above the tray. Surfaces other than concrete are placed in the tray as needed.

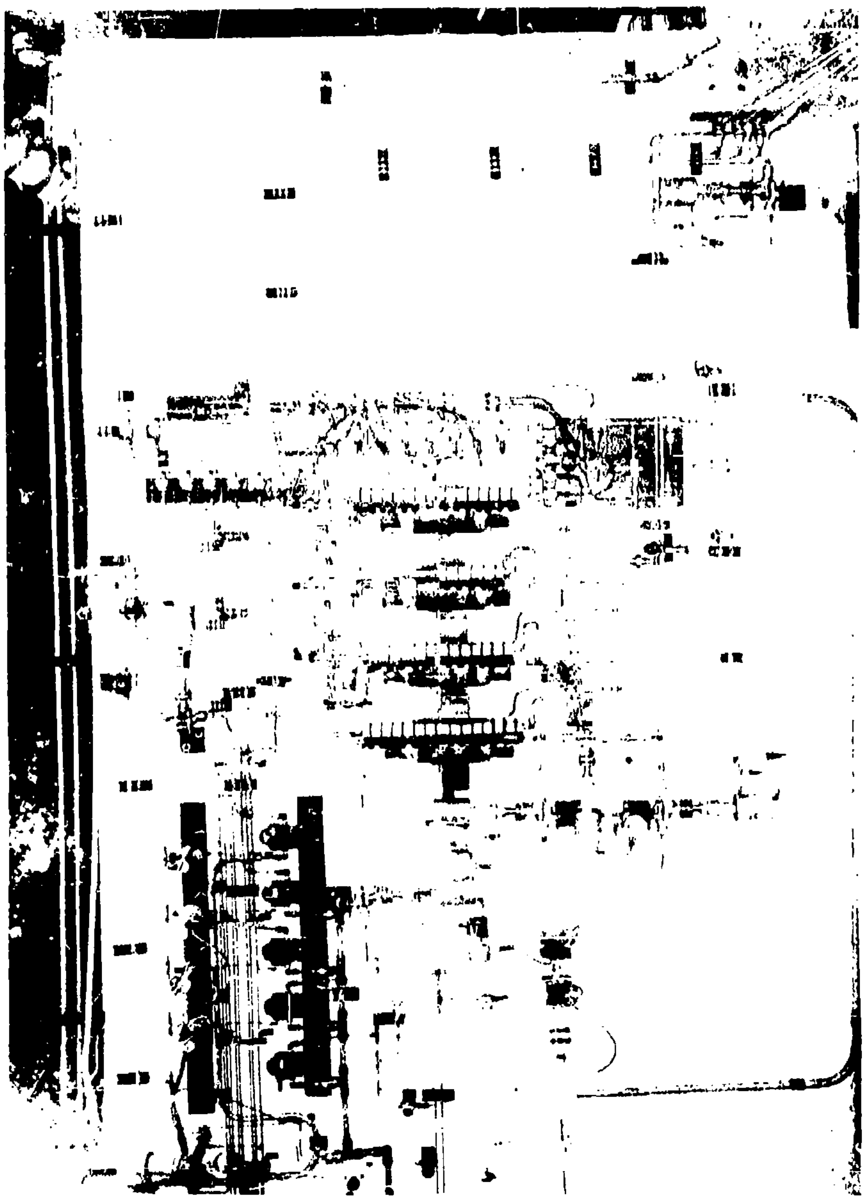


Figure 1. Small-Scale Hazard Determination Test System

1254-7/28/60-S1A

Figure 2. Propellant Spill Tray

Instrumentation

Because of the unexpected complexities in the interpretation of initial test results, pressure-sensing devices and photocells were installed for most of the propellant mixing spills. Two Photocon microphone transducers (Fig. 3), with ranges of approximately 5 psi, were employed to detect overpressure shocks. Sensor No. 1 (M-1) was located 10 feet from the point of contact with the face oriented directly toward the origin. Sensor No. 2 (M-2) was located 15 feet from the origin in a direct line with M-1.

Both transducers were mounted about one foot above ground level, i.e., in a plane about 14 to 18 inches above the actual contact surface. A Photocon 505 (lead sulfide) photocell was located about 10 feet from the point of origin also.

Ignition of the first flame of the reacting propellants was sensed by the photocell, while overpressure shocks were sensed by the microphone transducers. Signals generated by these devices were recorded on magnetic tape with an Ampex FR-107 FM recorder. The sound tape was replayed through a Tektronix 535A oscilloscope; photographs were taken of data of interest with a Polaroid Land Camera attachment to the oscilloscope. In addition, the tape was replayed at slow speed and significant data were re-recorded with a CEC galvanometer oscillograph. Ignition and overpressure data were compared with high-speed Fastax film to establish the sequence of significant events in the test results.

Visual results of these tests were recorded on color film with three high-speed motion picture cameras. A Fastax camera was focused on the immediate spill contact area and operated at 1000 frames per second; a Triad camera was used to scan the entire test area at 200 frames per second. Selected still-photographs of the results were printed from 70 mm film taken by a Hulscher camera, operated over a range of 6 to 20 frames per second, overlooking the test site. Ambient air temperature was measured with thermometers suspended in the general laboratory area, while

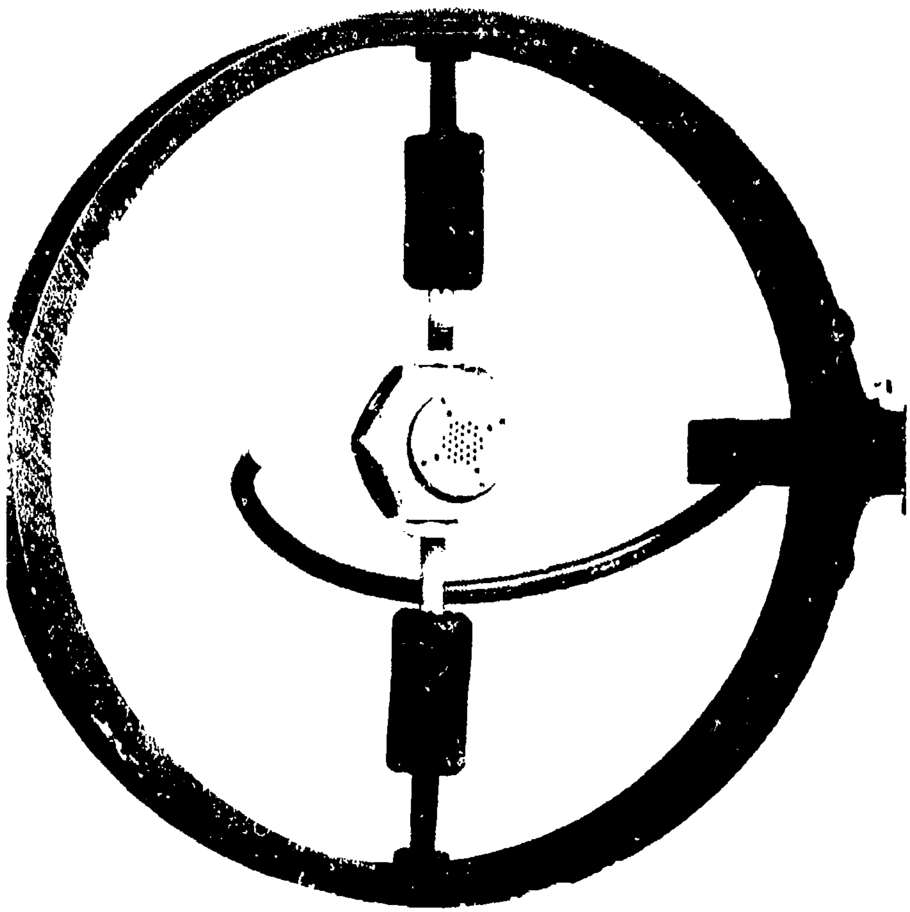


Figure 7. Photocon Microphone Transducer and Mounting Assembly

humidity and wind velocity were monitored and recorded by the Rocketdyne Test Operations Control Center.

Test Results

The small-scale spill tests were completed 23 January 1961. The quantitative results of these small-scale tests performed during the quarter ending 31 January 1961 are presented.

Chlorine Trifluoride and Hydrazine. Chlorine trifluoride was spilled with hydrazine on dry concrete; in each of the three sequence variations ignition occurred upon contact of the fuel and oxidizer. With simultaneous arrival, four distinct overpressure shocks were detected at each of the microphone transducer stations. The largest overpressure (ca. 0.171 psi) (Fig. 4), was detected at M-1 near the end of the actual propellant flows. A one-second lead of hydrazine produced comparable effects; the peak overpressure was 0.231 psi (Fig. 5). In both cases, overpressure amplitude at M-2 was, on the average, 50 to 60 percent of that at M-1. No overpressure shock was detected for a spill on dry concrete with an oxidizer lead.

A 2-inch-deep layer of dirt was placed in the spill basin and spills of this combination were continued. Both a simultaneous spill and a hydrazine lead test exhibited immediate ignition, smooth burning and very slight overpressure effects at M-1. Reaction with no measurable overpressure was observed with a chlorine trifluoride lead.

The dirt layer was removed and replaced with two inches of water. The simultaneous spill ignited and produced a series of overpressure shocks which reached a peak amplitude of 0.490 psi (Fig. 6). A lead of

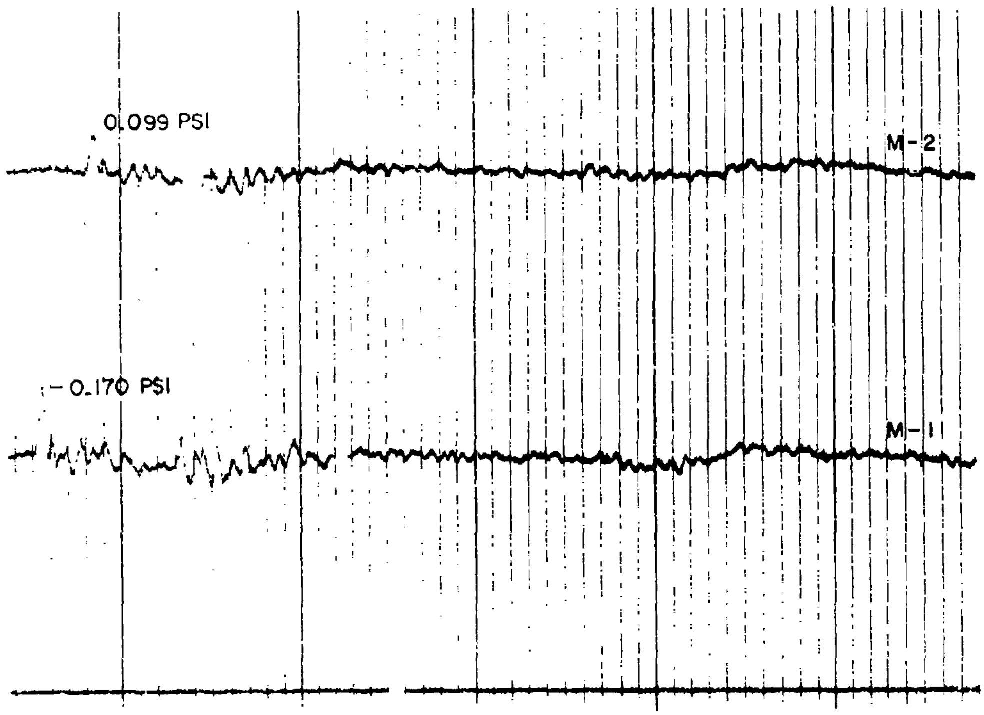


Figure 4. Overpressures from Simultaneous Spill of Chloride Trifluoride and Hydrazine on Concrete

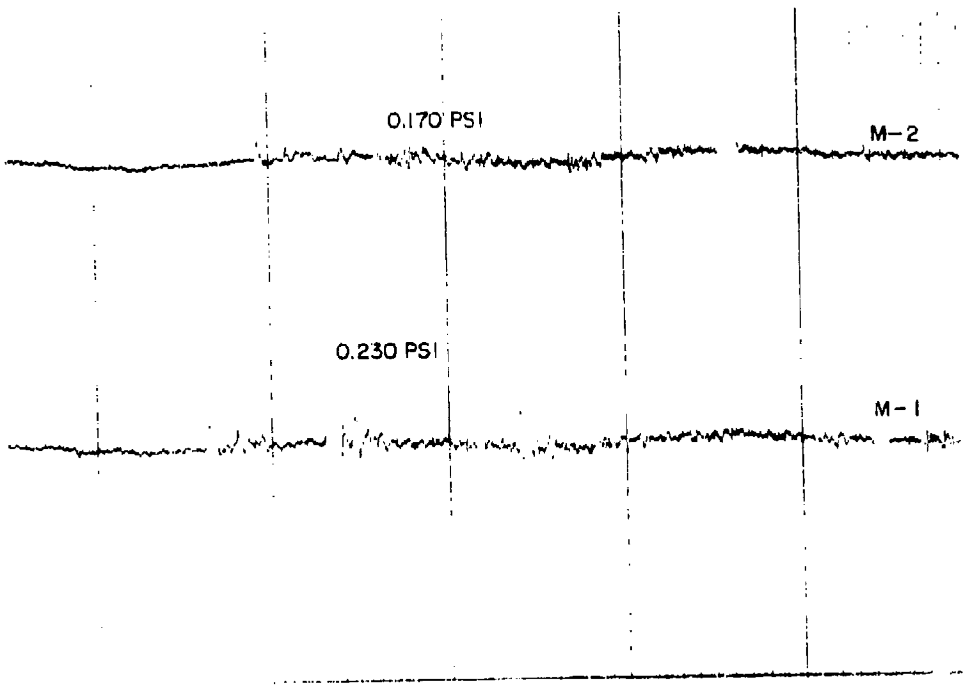


Figure 5. Overpressures from Hydrazine Lead of Chlorine Trifluoride on Concrete

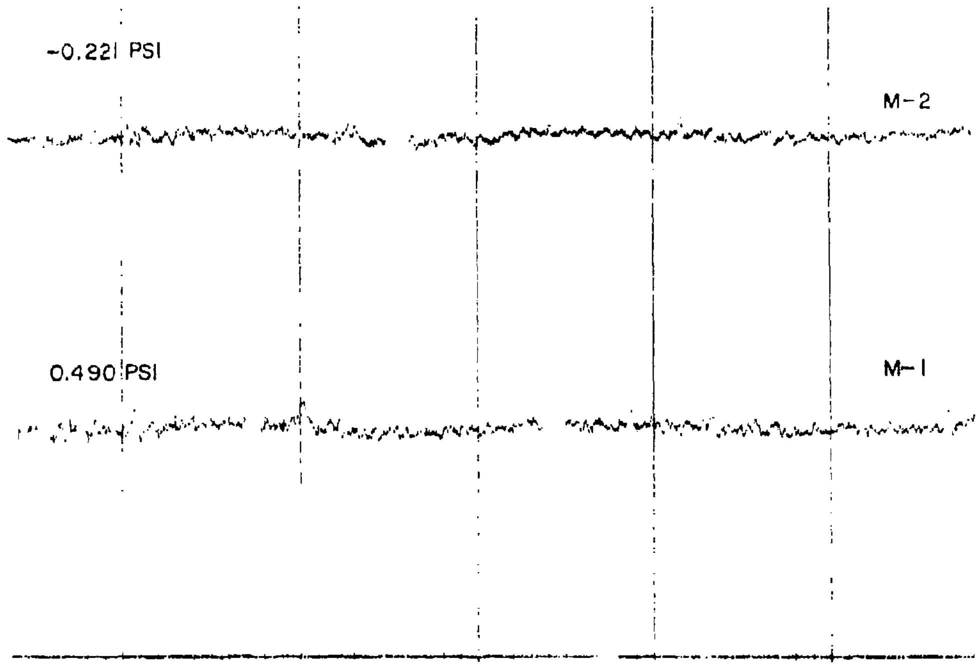


Figure 6. Overpressures from Simultaneous Spillage of Chlorine Trifluoride and Hydrazine on Water

hydrazine generated several minor overpressure disturbances over a period of several hundred milliseconds; a maximum overpressure of 0.126 psi occurred about midway through the propellant flow interval (Fig. 7). Overpressures as high as 0.178 psi (Fig. 8) were observed near the end of the test with a chlorine trifluoride lead. In the latter test, the frequency of overpressure shocks was higher than for the simultaneous spill and hydrazine-lead test.

A simultaneous spill of chlorine trifluoride and hydrazine on asphalt resulted in several minor overpressure shocks; the largest was 0.141 psi. A test with a one-second hydrazine lead generated only one measurable overpressure, while the subsequent test with an oxidizer lead produced only trace overpressures. In all sequences, chlorine trifluoride appeared to react with the asphalt and caused disintegration and burning at the surface.

In all tests with the chlorine trifluoride/hydrazine propellant combination, the photocell employed to detect the reaction failed to function properly. Thus, it was not possible to identify the time sequence of initial reaction and overpressure shocks. However, photographic records indicate that the overpressure shocks were the result of reactions occurring several feet above the spill surface. Further, these reactions were characterized by bright flashes, starting a few milliseconds after ignition, in the product gas cloud above the spill basin.

Chlorine Trifluoride and Nitrogen Tetroxide. A combined spill of the two oxidizers failed to exhibit any reaction on dry concrete. Both propellants were depleted by boiloff within a few minutes of the test. The three lead sequences showed no differences whatsoever. The combination also was spilled simultaneously on water. There was no visible or detectable reaction; even the characteristic "crackling" of the chlorine

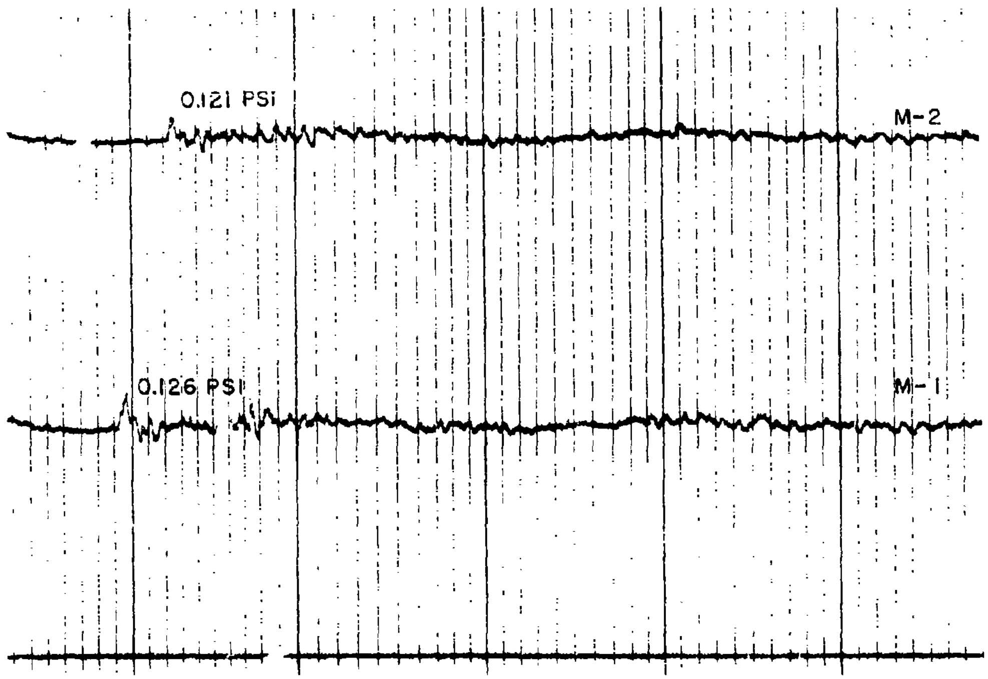


Figure 7. Overpressures from Hydrazine Lead of Chlorine Trifluoride on Water

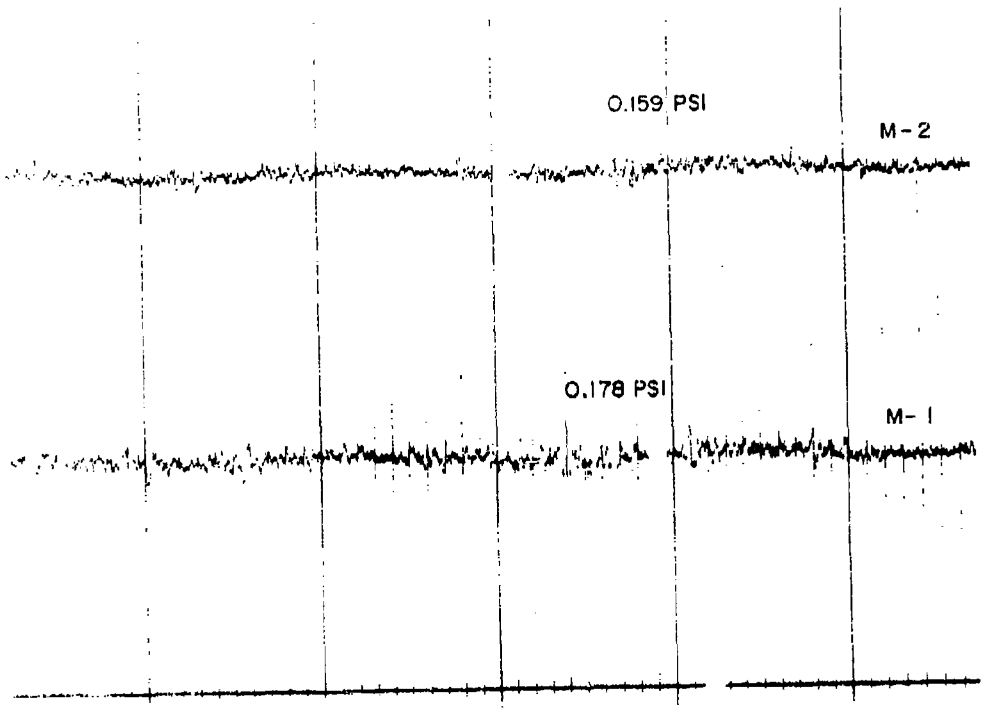


Figure 8. Overpressures from Chlorine Trifluoride Lead with Hydrazine on Water

trifluoride-water reaction was not evidenced. With these tests, it was concluded that no reaction of any consequence would result from mixing of these propellants; therefore, further testing of this combination was canceled.

Chlorine Trifluoride and Pentaborane. This combination was spilled first on a dry concrete surface. Simultaneous spillage and an oxidizer lead on this surface resulted in instantaneous ignition, smooth burning and no measurable overpressures. A one-second lead of pentaborane produced three distinct, minor overpressure shocks. However, the first peak was the result of pentaborane ignition with air, at the concrete surface, prior to the appearance of chlorine trifluoride (Fig. 9). The reaction of pentaborane at the spill contact surface was attributed, in part, to the fact that the surface was still warm from the preceding test.

A simultaneous spill of chlorine trifluoride and pentaborane and a fuel lead, on dirt, resulted in immediate ignition, smooth burning and no evidence of overpressure. Several small overpressure peaks, of which only three were measurable, were observed during a combined spill with a one-second oxidizer lead.

Similar results were recorded when the dirt was replaced by an asphalt surface. No overpressure shocks were encountered following a simultaneous spill or a test with a pentaborane lead. Overpressures as high as 0.147 psi (Fig. 10) resulted from a chlorine trifluoride lead. As noted before, the oxidizer reacted with asphalt to produce some deterioration of the surface.

All three sequences employing this combination, on water, resulted in a series of overpressure shocks during the tests. Maximum overpressure

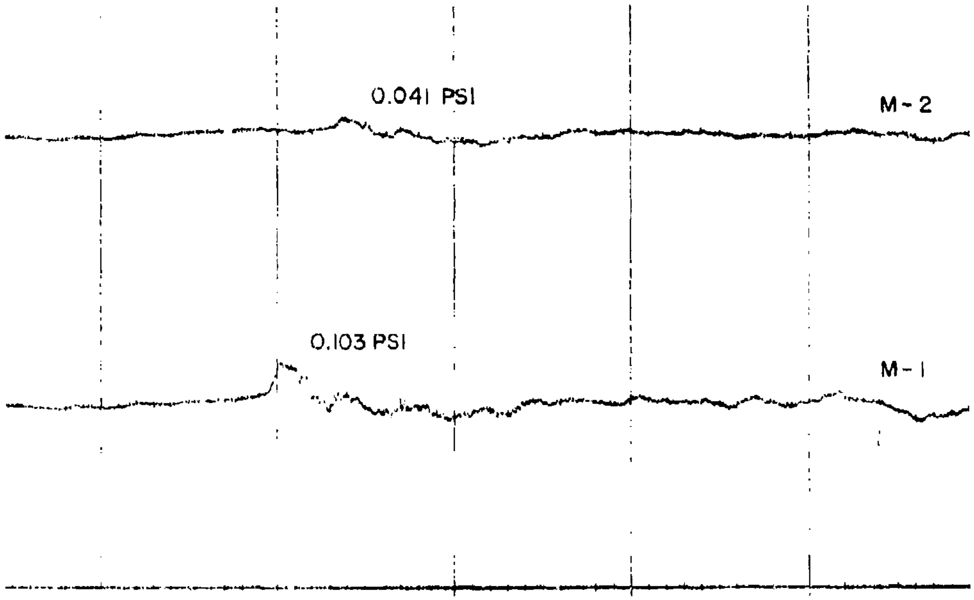


Figure 9. Overpressure Resulting from Pyrophoric Ignition of Pentaborane

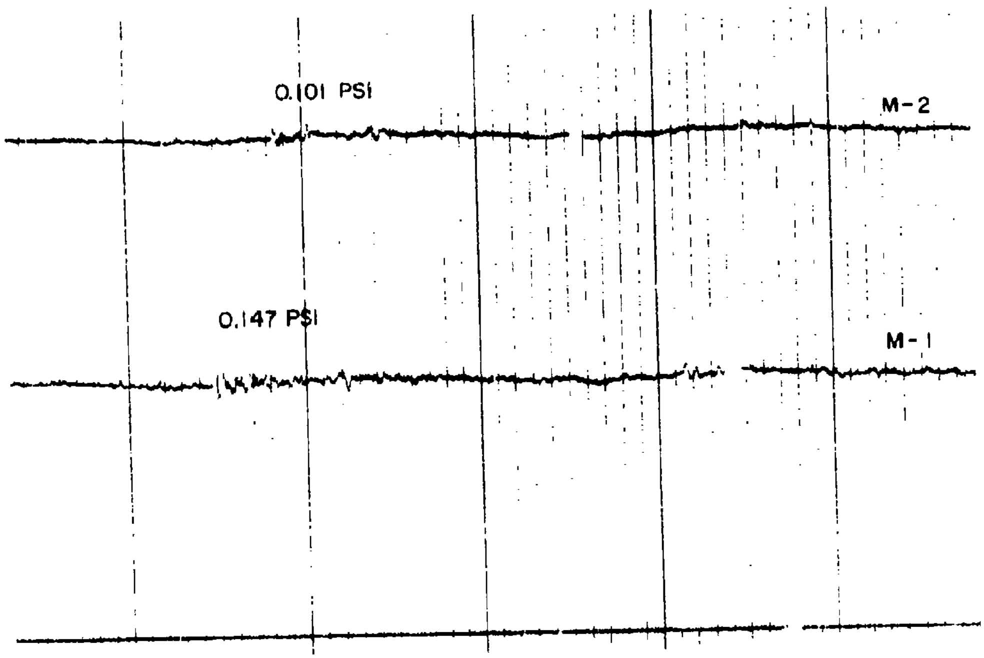


Figure 10. Overpressure Resulting from Chlorine Trifluoride Lead with Pentaborane on Asphalt

amplitudes of 0.114, 0.048, and 0.106 psi were recorded for the simultaneous spill, pentaborane lead and chlorine trifluoride lead, respectively. In each of these tests, the propellants appeared to burn on the surface of the water until the pentaborane was depleted.

The photocell failed again to operate properly during this series of tests. As before, accurate over-all sequencing of the data was not possible. The photographic evidence for reactions taking place in the product cloud above the spill basin was repeated.

<u>Nitrogen Tetroxide and Hydrazine</u>. Although several uninstrumented spills of nitrogen tetroxide and hydrazine had been made previously, it was decided that this series should be repeated for the purpose of making measurements of overpressure amplitudes. Combination spills were made first on dry concrete. Approximately 8.75 milliseconds after the photocell recorded ignition in a simultaneous spill, an overpressure of 0.454 psi was detected at M-1 (Fig. 11). The speed of sound under the ambient test conditions was 1127 feet per second, corresponding to an interval of 8.88 milliseconds for sound to traverse the 10 feet between the origin and M-1. A shock strength of 0.191 psi was recorded at M-2, 4.45 milliseconds later. This time delay was in good agreement with the speed of sound computation, also. Two additional shocks of 0.182 and 0.819 psi were detected by M-1 at 0.113 and 0.430 seconds after ignition (photocell), respectively.

A hydrazine lead on the concrete surface generated a series of overpressure shocks in the time interval between 0.075 and 0.536 seconds after ignition. Amplitudes as great as 2.000 psi were attained at two points in this test. Several weak shocks were recorded in a spill of the combination with an oxidizer lead. A trace overpressure was detected at 9.25 milliseconds after photocell activation; shock amplitudes of 0.910 psi

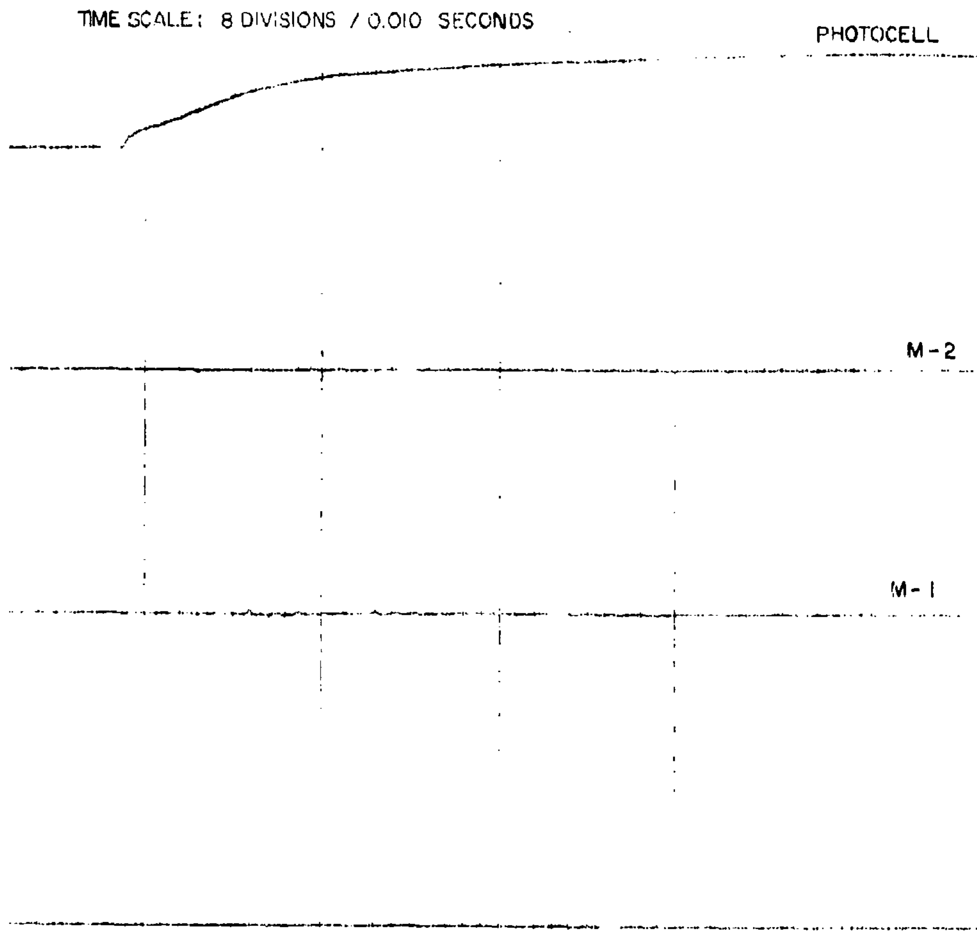


Figure 11 Overpressure Resulting from Simultaneous Spill of Hydrazine and Nitrogen Tetroxide On Dry Concrete

were encountered at 38 and 56 milliseconds, successively (Fig. 12), and a peak of 1.000 psi was recorded 217 milliseconds after ignition.

The same spill sequences were repeated on an asphalt surface. No pressure effects were recorded during a test beginning with a simultaneous spill of nitrogen tetroxide and hydrazine. A fuel lead resulted in a series of overpressure shocks, which reached an amplitude of 1.545 psi several hundred milliseconds after ignition. A combined spill with a nitrogen tetroxide lead produced immediate ignition and a series of overpressure shocks (Fig. 13); these were concluded approximately 60 milliseconds after initial appearance.

Overpressure was recorded 38 milliseconds after the ignition of a simultaneous spill on dirt. A few hundred milliseconds later a series of shocks that reached 1.455 psi were observed. Five overpressure shocks, with amplitudes as high as 1.910 psi (Fig. 14) were recorded after a hydrazine lead on dirt. A nitrogen tetroxide lead on dirt generated a series of shocks that continued until 0.825 seconds after ignition. A maximum overpressure of 1.728 psi occurred 0.533 seconds after ignition.

The concrete spill basin was flushed thoroughly and filled with two inches of water. A simultaneous spill of nitrogen tetroxide and hydrazine yielded five overpressure shocks at 52, 108, 326, 382, and 419 milliseconds after ignition, respectively; the maximum overpressure was 1.819 psi. Several overpressure shocks, in the period from 49 to 485 milliseconds after ignition, accompanied a combined spill on water with a hydrazine lead. The test on water, with an oxidizer lead, employed twice as much total propellant as had been used previously. Thus, overpressures were observed as late as 0.969 seconds after ignition. However, the maximum overpressure of 1.046 psi occurred only 46 milliseconds after ignition.

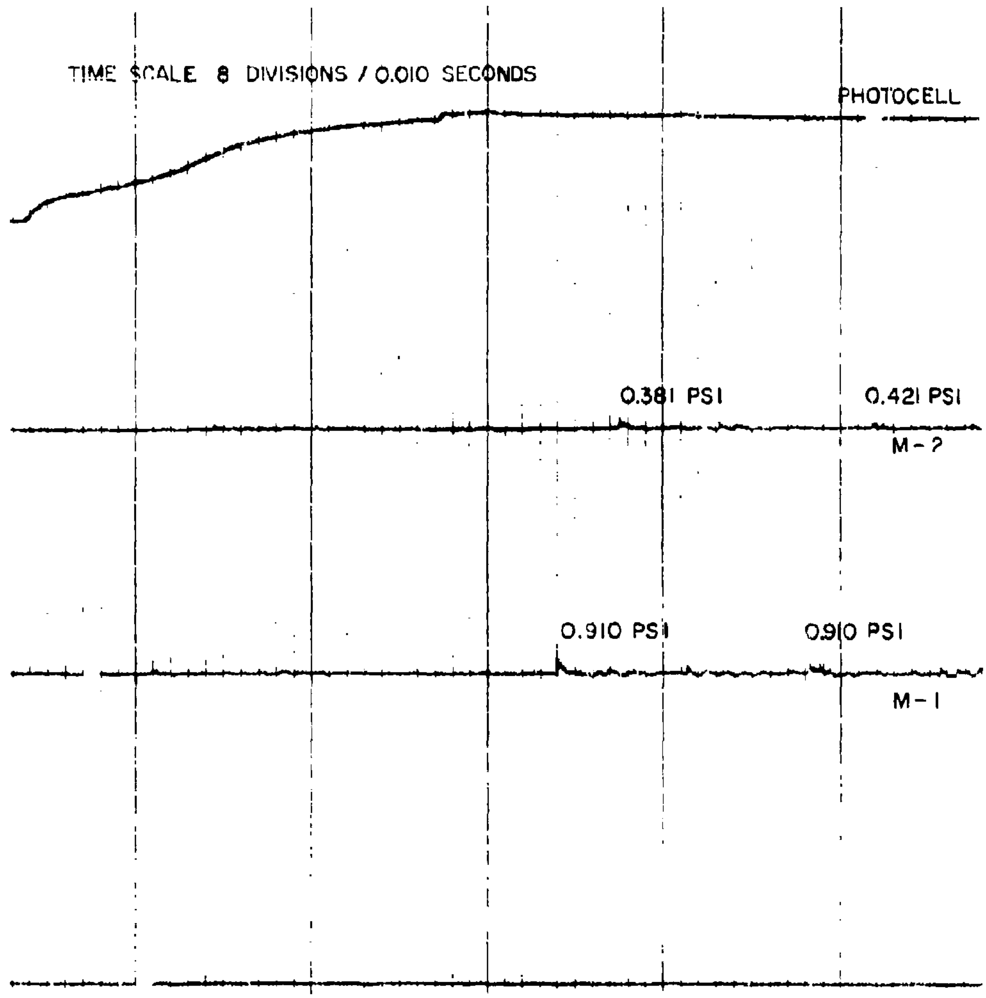


Figure 12. Overpressure Resulting from Nitrogen Tetroxide Lead with Hydrazine on Dry Concrete

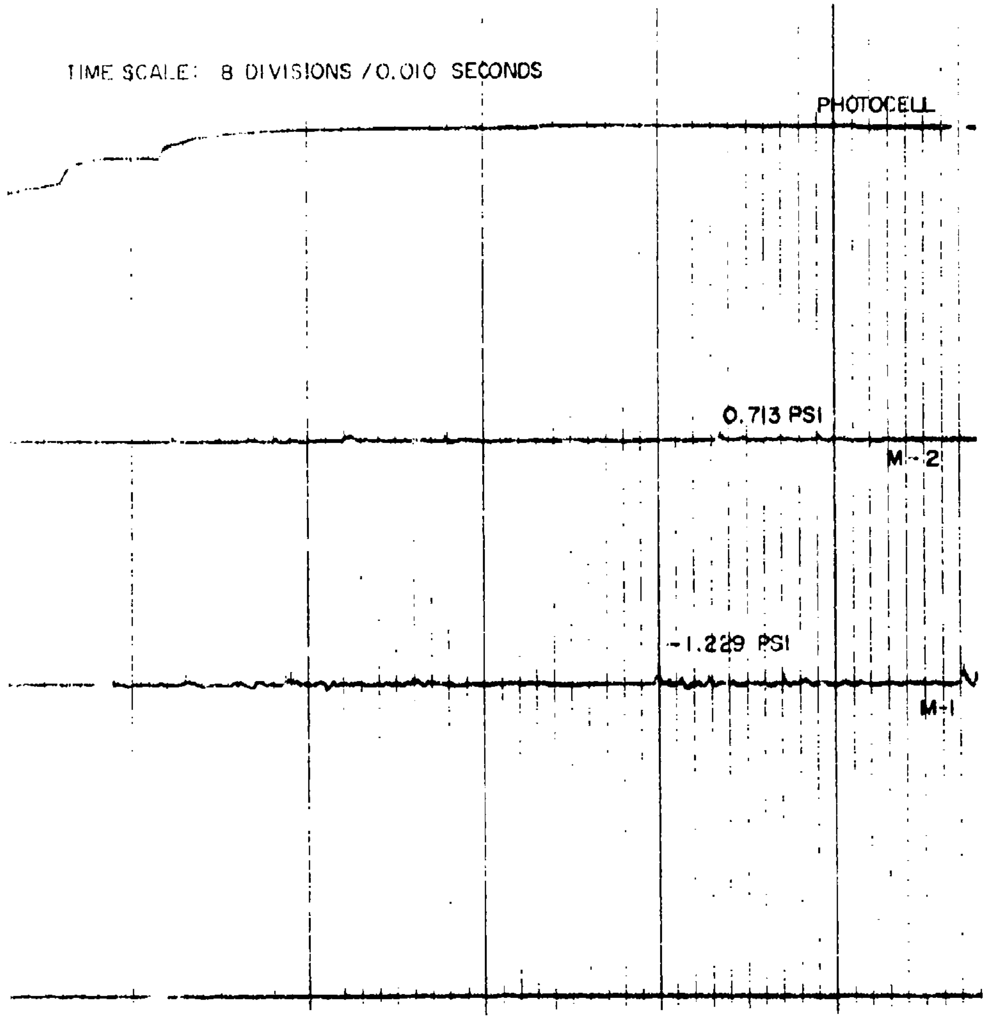


Figure 13. **Overpressure Resulting from Nitrogen Tetroxide Lead with Hydrazine on Asphalt**

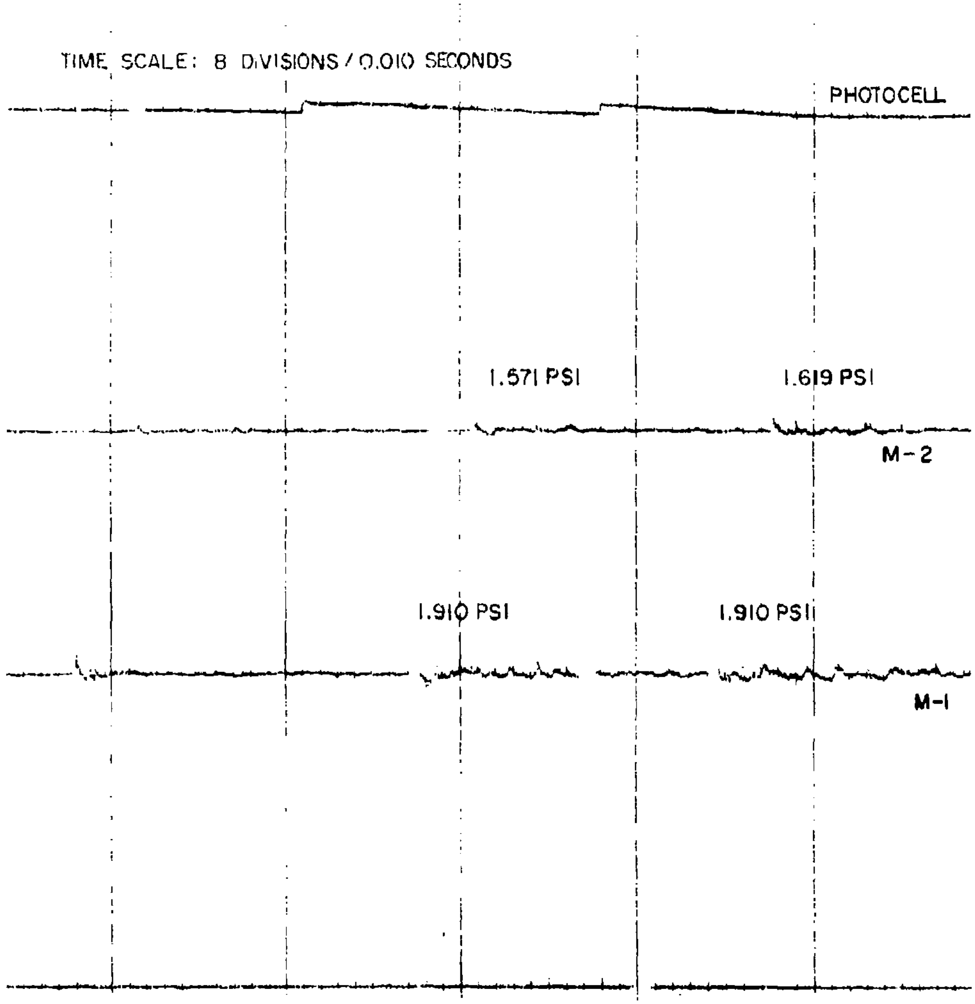


Figure 14. Overpressure Resulting from Hydrazine Lead with Nitrogen Tetroxide on Dirt

In all of the nitrogen tetroxide and hydrazine spill tests, ignition occurred immediately upon contact. The majority of these tests was accompanied by an extended series of overpressure shocks; the source of the explosions appeared to be an area about two to four feet above the spill contact surface. Color motion pictures clearly defined bright, white flashes originating in the product gas cloud above the actual propellant fire. Data were correlated by comparison of the time bases for the magnetic tape and Fastax film. In every instance, it was found that the flashes recorded photographically were related directly to the overpressures sensed by the microphone transducers.

Hydrazine and Pentaborane. Several of the initial spills with this combination were repeated with full instrumentation. First, the combination was spilled simultaneously on concrete; ignition occurred after a short delay and a slight overpressure was detected at M-1. Subsequent burning was rapid and smooth; a lead of pentaborane on the same surface produced identical results. With a hydrazine lead on concrete, the propellants appeared to ignite on contact and began to burn smoothly. About two seconds after the photocell first sensed ignition, the photocell detected a second increase in radiation intensity and overpressures of 2.635 and 2.155 psi were observed at M-1 and M-2, respectively (Fig. 15). However, the shock wave was recorded at M-1; only six milliseconds after the step-change in intensity at the photocell. As noted previously, a shock traveling at the speed of sound requires 8.8 milliseconds to traverse the 10 feet between the spill basin and M-1. In this case also, the time delay between detection at M-1 and M-2 agreed with the calculated value of 4.5 milliseconds (Fig. 15). Later examination of motion pictures showed that this explosion took place in conjunction with the post-test propellant purges.

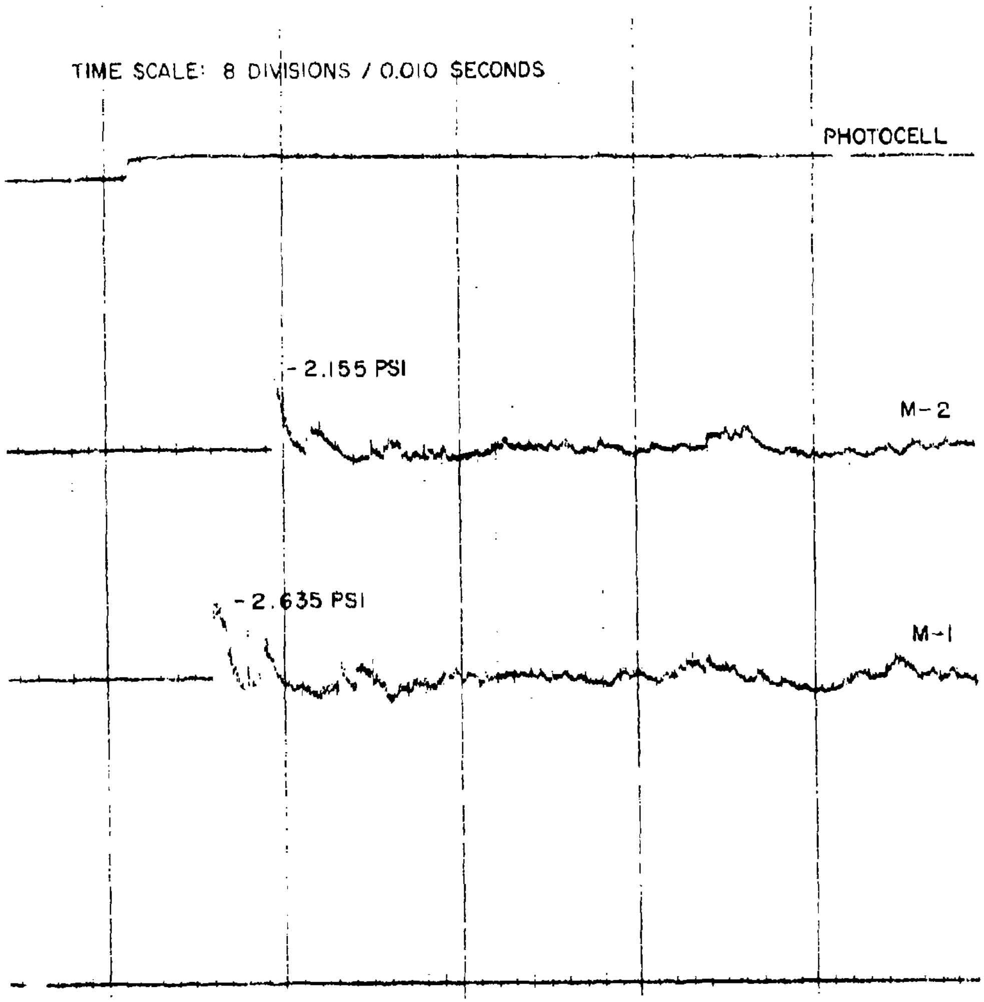


Figure 15. Overpressure Resulting from a Hydrazine Lead with Pentaborane on Dry Concrete

Two combined hydrazine and pentaborane spills were carried out on an asphalt surface. Simultaneous spillage resulted in a large explosion after an appreciable delay in reaction; overpressure was recorded at M-1, 6.25 milliseconds after photocell activation (Fig. 16). The explosion threw asphalt several feet through the surrounding test area. Overpressure amplitudes of 2.365 and 2.423 psi were observed at M-1 and M-2, respectively. A lead of pentaborane on asphalt resulted in a comparable ignition delay and large explosion. An overpressure of 2.455 psi was detected at M-1, 12.5 milliseconds after the photocell sensed ignition; the shock strength at M-2 was 2.463 psi (Fig. 17). The asphalt was fragmented and scattered as before. In both tests, the shock transit time between stations M-1 and M-2 was the theoretical 4.5 milliseconds.

The asphalt was replaced by two inches of dirt in the concrete spill basin. Simultaneous spillage of hydrazine and pentaborane on dirt produced a slight ignition delay and smooth burning until 0.205 seconds after photocell activation. At that time, the photocell sensed a second increase in intensity; 5.25 milliseconds later, M-1 sensed an overpressure of 2.365 psi. An overpressure of 2.230 psi was recorded at M-2, 4.5 milliseconds later (Fig. 18). A pentaborane lead gave the same sequence of events. An overpressure of 2.500 psi was observed at M-1, 10.5 milliseconds after the photocell indicated ignition (Fig. 19). The same shock was recorded as 2.650 psi at M-2 after the usual delay.

All tests with hydrazine and pentaborane were characterized by an appreciable delay in the initial reaction; ca. 30 to 40 milliseconds. In tests of other combinations, the origin of overpressure shocks appeared to be in the product gas cloud above the spill basin. With this combination, however, the origin appeared to be located at the contact surface or within the confines of the spill basin. Certain other anomalies were encountered also. Time delays between photocell activation and shock

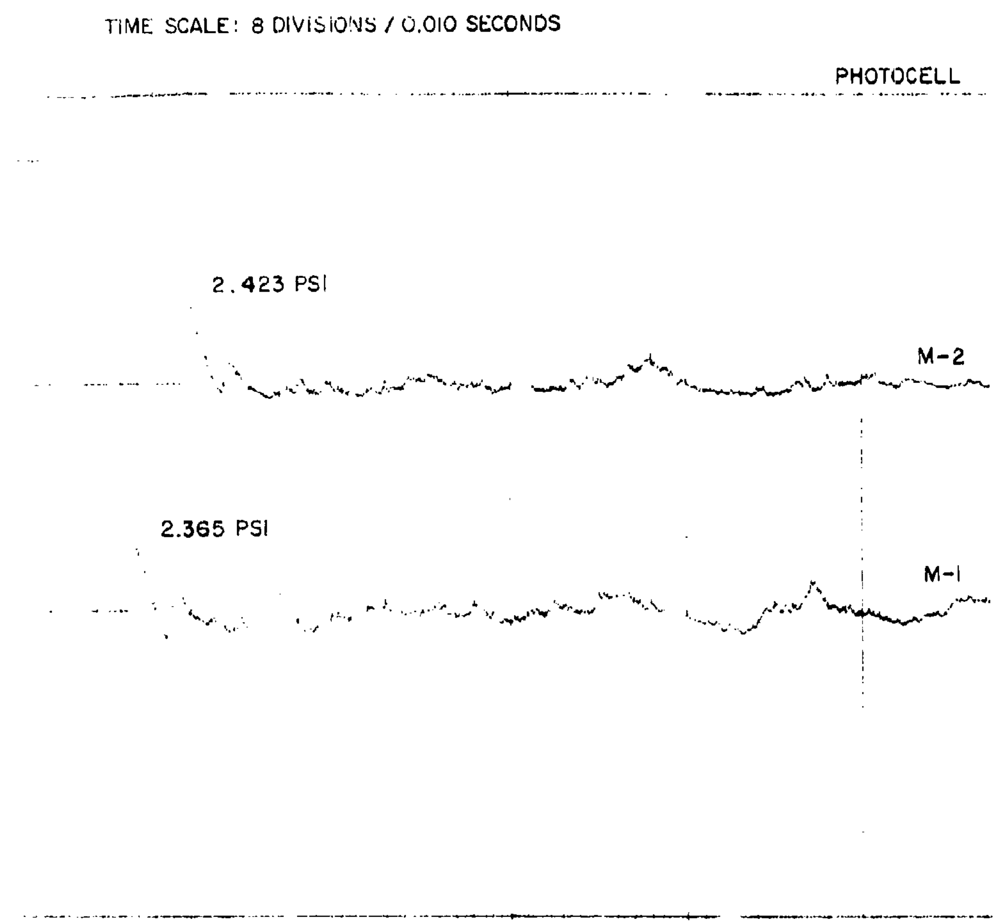


Figure 16. Overpressure Resulting from a Simultaneous Spill of Hydrazine and Pentaborane on Asphalt

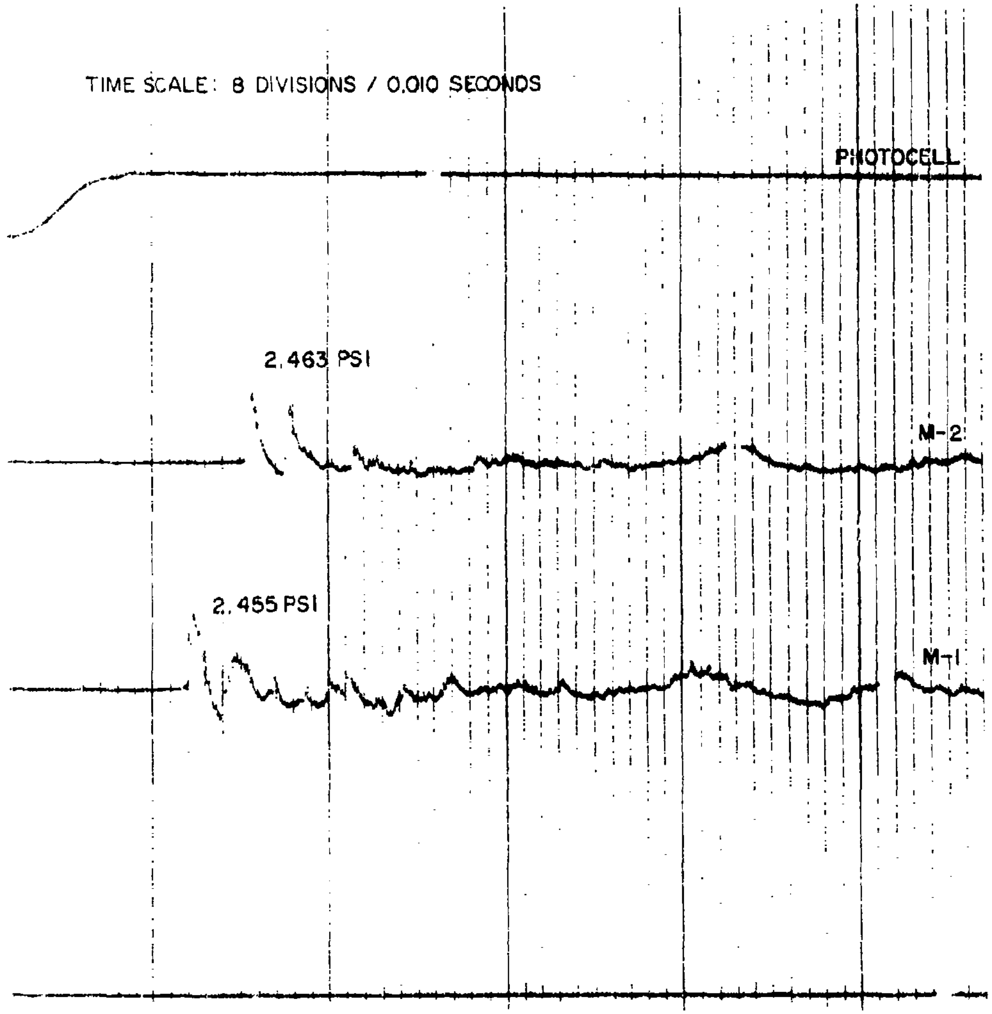


Figure 17. Overpressure Resulting from a Pentaborane Lead with Hydrazine on Asphalt

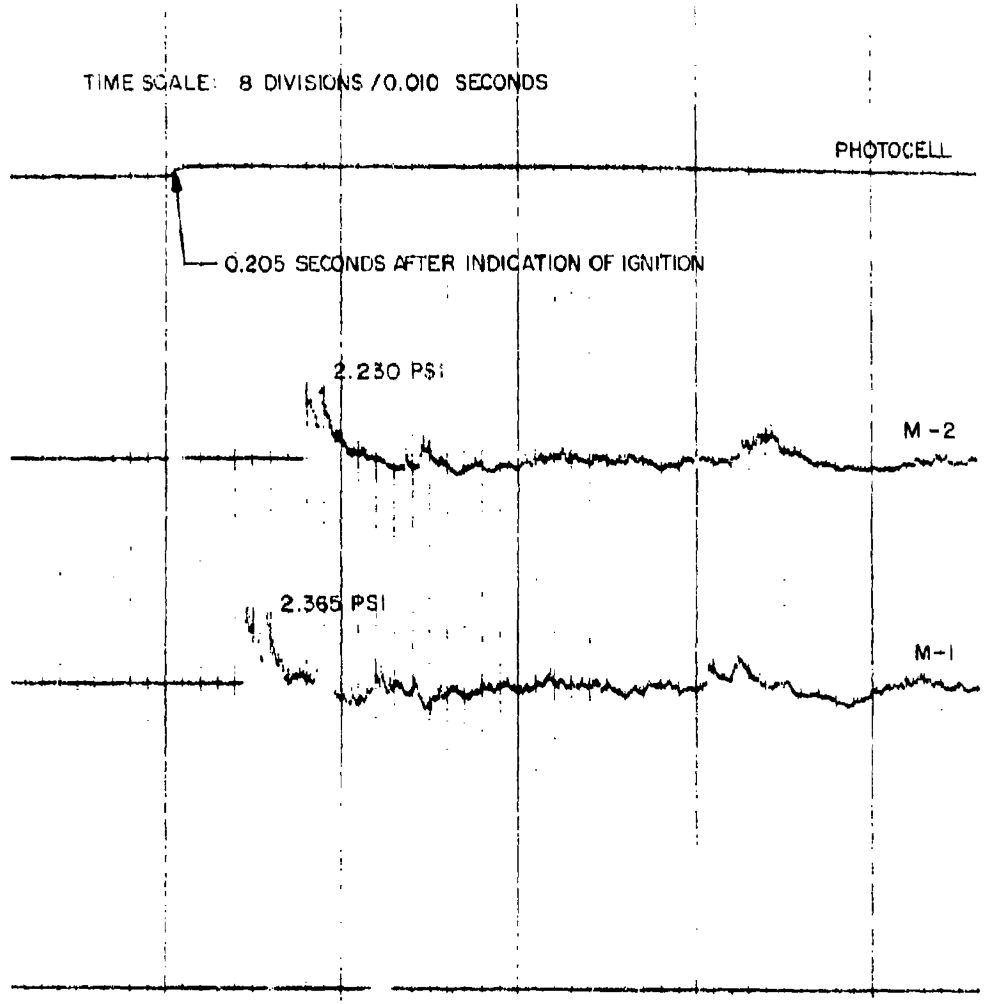


Figure 18. Overpressure Resulting from Simultaneous Spill of Hydrazine and Pentaborane on Dirt

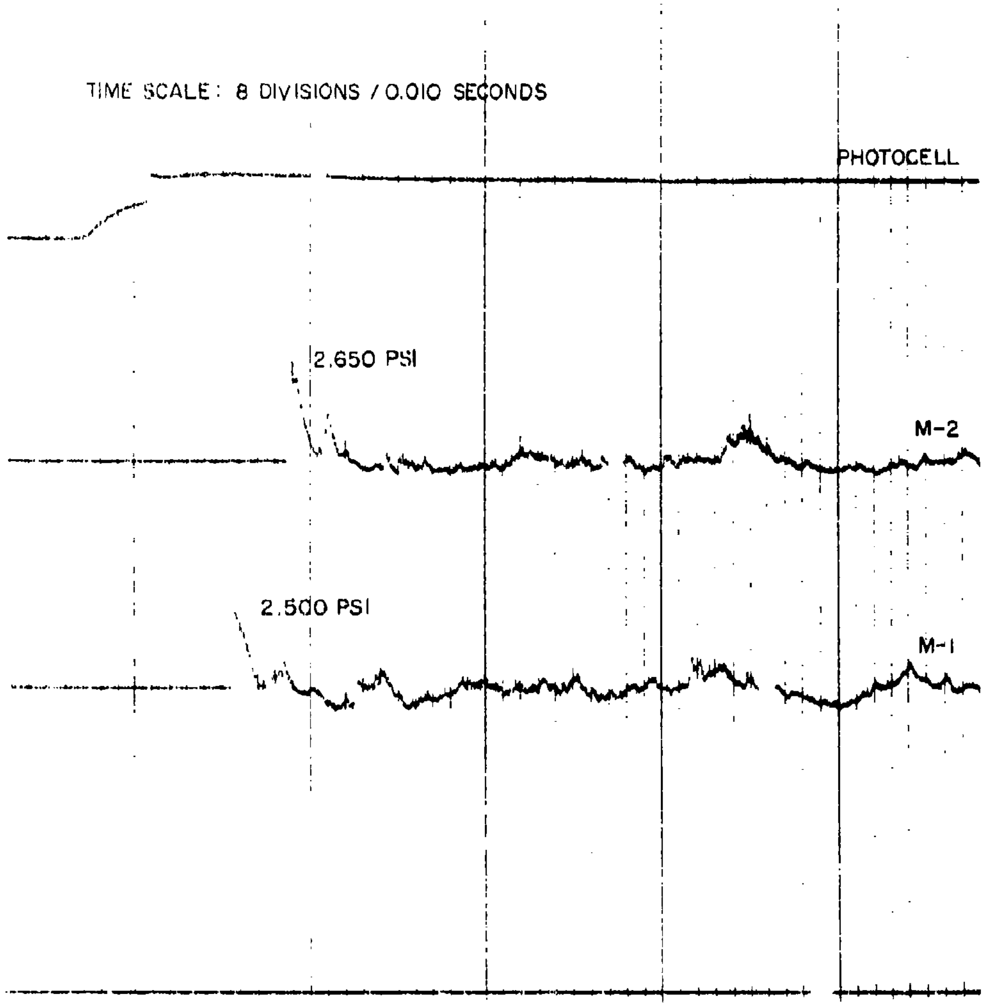


Figure 19. Overpressure Resulting from Pentaborane Lead with Hydrazine on Dirt

interaction at M-1 were consistently less than the predicted 8.8 milliseconds. Conversely, shock transition times between M-1 and M-2 were in good agreement with theory. Finally, shock strengths were equal at stations M-1 and M-2, rather than 40 to 60 percent less as observed for other propellant combinations and as predicted from TNT equivalence tables.

The results of all instrumented combined spill tests are summarized in Table 1.

TABLE 1

RESULTS OF INSTRUMENTED COMBINED SPILL TESTS

Chlorine Trifluoride and Hydrazine

Test No. 27 - Simultaneous Spill on Dry Concrete

Temperature, 62 F; Rel. Humidity, 13 percent

W_{CTF}, 1.8 lb; W_{HZ}, 1.0 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_1	0.030	0.015
t_2	0.111	0.061
t_3	0.156	0.076
t_4	0.171	0.099

Test No. 28 - Hydrazine Lead on Dry Concrete

Temperature, 62 F; Rel. Humidity, 13 percent

W_{CTF}, 1.8 lb; W_{HZ}, 1.3 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_1	0.047	0.030
t_2	0.096	0.046
t_3	0.130	0.092
t_4	0.230	0.107

TABLE 1

(Continued)

Test No. 29 - Chlorine Trifluoride Lead on Dry Concrete

Temperature, 62 F; Rel. Humidity, 13 percent

W_{CTF}, 2.4 lb; W_{HZ}, 1.0 lb

No Detectable Overpressure

Test No. 33 - Simultaneous Spill on Dirt

Temperature, 60 F; Rel. Humidity, 14 percent

W_{CTF}, 1.8 lb; W_{HZ}, 1.0 lb

Trace Overpressure

Test No. 34 - Hydrazine Lead on Dirt

Temperature, 60 F; Rel. Humidity, 14 percent

W_{CTF}, 1.8 lb; W_{HZ}, 1.3 lb

Trace Overpressure

Test No. 35 - Chlorine Trifluoride on Dirt

Temperature, 60 F; Rel. Humidity, 15 percent

W_{CTF}, 2.4 lb; W_{HZ}, 1.0 lb

No Detectable Overpressure

Test No. 36 - Simultaneous Spill on Water

Temperature, 59 F; Rel. Humidity, 15 percent

W_{CTF}, 1.8 lb; W_{HZ}, 1.0 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_1	0.044	0.030
t_2	0.490	0.221
t_3	0.237	0.099

TABLE 1
(Continued)

Test No. 36 (continued)

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_4	0.133	0.091
t_5	0.156	0.099
t_6	0.104	0.053
t_7	0.319	0.162

Test No. 37 - Hydrazine Lead on Water
Temperature, 58 F; Rel. Humidity, 15 percent
W_{CTF}, 1.8 lb; W_{HZ}, 1.5 lb

Time, sec	Overpressure, psi	
	Station M-1 f	Station M-2
t_1	0.096	0.057
t_2	0.082	0.069
t_3	0.126	0.121
t_4	0.119	0.107
t_5	0.067	0.046

Test No. 38 - Chlorine Trifluoride Lead on Water
Temperature, 58 F; Rel. Humidity, 16 percent
W_{CTF}, 2.4 lb; W_{HZ}, 1.0 lb

TABLE 1

(Continued)

Test No. 38 (continued)

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_1	0.033	0.023
t_2	0.081	0.053
t_3	0.100	0.083
t_4	0.148	0.068
t_5	0.156	0.076
t_6	0.178	0.159
t_7	0.174	0.129

Test No. 40 - Simultaneous Spill on Asphalt

Temperature, 57 F; Rel. Humidity, 16 percent

W_{CTF}, 1.8 lb; W_{HZ}, 1.0 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_1	0.104	0.046
t_2	0.104	0.061
t_3	0.141	0.083

Test No. 41 - Hydrazine Lead on Asphalt

Temperature, 56 F; Rel. Humidity, 16 percent

W_{CTF}, 1.8 lb; W_{HZ}, 1.3 lb

TABLE 1

(Continued)

Test No. 41 (continued)

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_1	Trace	Trace
t_2	0.082	0.038
t_3	Trace	Trace

Test No. 42 - Chlorine Trifluoride on Asphalt

Temperature, 56 F; Rel. Humidity, 16 percent

W_{CTF}, 2.4 lb; W_{HZ}, 1.3 lb

Trace Overpressure

Chlorine Trifluoride and Nitrogen Tetroxide

Test No. 30 - Simultaneous Spill on Dry Concrete

Temperature, 61 F; Rel. Humidity, 13 percent

W_{CTF} , 1.8 lb; W_{NTO}, 1.5 lb

No Reaction

Test No. 31 - Nitrogen Tetroxide Lead on Dry Concrete

Temperature, 61 F; Rel. Humidity, 14 percent

W_{CTF}, 1.8 lb; W_{NTO}, 2.0 lb

No Reaction

Test No. 32 - Chlorine Trifluoride Lead on Dry Concrete

Temperature, 61 F; Rel. Humidity, 14 percent

W_{CTF}, 2.4 lb; W_{NTO}, 1.5 lb

No Reaction

TABLE 1
(Continued)

Test No. 39 - Simultaneous Spill on Water
Temperature, 57 F; Rel. Humidity, 16 percent
W_{CTF}, 1.8 lb; W_{NTO}, 1.5 lb
No Reaction

Chlorine Trifluoride and Pentaborane

Test No. 43 - Simultaneous Spill on Dry Concrete
Temperature, 70 F; Rel. Humidity, 9 percent
W_{CTF}, 1.8 lb; W_{PB}, 0.7 lb
No Detectable Overpressure

Test No. 44 - Pentaborane Lead on Dry Concrete
Temperature, 70 F; Rel. Humidity, 9 percent
W_{CTF}, 1.8 lb; W_{PB}, 0.9 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_1	0.103	0.041
t_2	0.082	0.030
t_3	0.139	0.101

Test No. 45 - Chlorine Trifluoride Lead on Dry Concrete
Temperature, 70 F; Rel. Humidity, 9 percent
W_{CTF}, 2.4 lb; W_{PB}, 0.7 lb
No Detectable Overpressure

TABLE 1
(Continued)

Test No. 46 - Simultaneous Spill on Dirt

Temperature, 70 F; Rel. Humidity, 9 percent

W_{CTF}, 1.8 lb; W_{PB}, 0.7 lb

No Detectable Overpressure

Test No. 47 - Pentaborane Lead on Dirt

Temperature, 70 F; Rel. Humidity, 9 percent

W_{CTF}, 1.8 lb; W_{PB}, 0.9 lb

No Detectable Overpressure

Test No. 48 - Chlorine Trifluoride Lead on Dirt

Temperature, 70 F; Rel. Humidity, 9 percent

W_{CTF}, 2.4 lb; W_{PB}, 0.7 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_1	0.051	0.030
t_2	0.066	0.041
t_3	0.103	0.051

Test No. 49 - Simultaneous Spill on Asphalt

Temperature, 70 F; Rel. Humidity, 9 percent

W_{CTF}, 1.8 lb; W_{PB}, 0.7 lb

No Detectable Overpressure

Test No. 50 - Pentaborane Lead on Asphalt

Temperature, 70 F; Rel. Humidity, 9 percent

W_{CTF}, 1.8 lb; W_{PB}, 0.9 lb

No Detectable Overpressure

TABLE 1
(Continued)

Test No. 51 - Chlorine Trifluoride Lead on Asphalt
Temperature, 70 F; Rel. Humidity, 9 percent
W_{CTF}, 2.4 lb; W_{PB}, 0.7 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_1	0.103	0.061
t_2	0.147	0.101
t_3	0.051	0.051
t_4	0.114	0.086
t_5	0.059	0.041

Test No. 52 - Simultaneous Spill on Water
Temperature, 70 F; Rel. Humidity, 9 percent
W_{CTF}, 1.8 lb; W_{PB}, 0.7 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_1	0.066	0.041
t_2	0.073	0.046
t_3	0.114	0.071
t_4	0.059	0.035

TABLE 1
(Continued)

Test No. 53 - Pentaborane Lead on Water
Temperature, 70 F; Rel. Humidity, 9 percent
W_{CTF}, 1.8 lb; W_{PB}, 0.9 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_1	0.048	0.035
t_2	0.037	0.020

Test No. 54 - Chlorine Trifluoride Lead on Water
Temperature, 70 F; Rel. Humidity, 9 percent
W_{CTF}, 2.4 lb; W_{PB}, 0.7 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_1	0.106	0.071
t_2	0.092	0.061
t_3	0.106	0.071
t_4	0.070	0.061
t_5	0.051	0.041
t_6	0.103	0.066

Nitrogen Tetroxide and Hydrazine

Test No. 55 - Simultaneous Spill on Dry Concrete
Temperature, 67 F; Rel. Humidity, 12 percent
W_{NTO}, 1.5 lb; W_{HZ}, 1.0 lb

TABLE 1
(Continued)

Test No. 55 (continued)

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
0.00875	0.454	0.191
0.113	0.182	0.048
0.430	0.819	0.333

Test No. 56 - Hydrazine Lead on Dry Concrete
Temperature, 67 F; Rel. Humidity, 12 percent
W_{NTO}, 1.5 lb; W_{HZ}, 1.3 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
0.075	0.346	0.191
0.117	1.955	1.381
0.143	2.000	1.620
0.187	0.728	0.619
0.264	0.818	0.904
0.299	1.455	0.762
0.371	1.685	1.142
0.399	2.000	1.810
0.456	1.639	1.142
0.536	1.639	0.953

TABLE 1
(Continued)

Test No. 57 - Nitrogen Tetroxide Lead on Dry Concrete
Temperature, 67 F; Rel. Humidity, 12 percent
W_{NTO}, 2.0 lb; W_{HZ}, 1.0 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
0.00925	Trace	Trace
0.038	0.910	0.381
0.056	0.910	0.428
0.217	1.000	0.667

Test No. 58 - Simultaneous Spill on Asphalt
Temperature, 67 F; Rel. Humidity, 12 percent
W_{NTO}, 1.5 lb; W_{HZ}, 1.0 lb
No Detectable Overpressure

Test No. 59 - Hydrazine Lead on Asphalt
Temperature, 67 F; Rel. Humidity, 12 percent
W_{NTO}, 1.5 lb; W_{HZ}, 1.3 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
t_1	0.409	0.143
t_2	0.682	0.333
t_3	1.545	0.667

TABLE 1
(Continued)

Test No. 60 - Nitrogen Tetroxide Lead on Asphalt

Temperature, 67 F; Rel. Humidity, 12 percent

W_{NTO}, 2.0 lb; W_{HZ}, 1.0 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
0.0089	0.636	0.286
0.048	1.229	0.713
0.069	1.091	0.666

Test No. 61 - Simultaneous Spill on Dirt

Temperature, 67 F; Rel. Humidity, 12 percent

W_{NTO}, 1.5 lb; W_{HZ}, 1.0 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
0.038	0.546	0.238
0.356	0.454	0.191
0.379	1.455	0.762
0.403	0.773	0.381
0.446	1.091	0.524

Test No. 62 - Hydrazine Lead on Dirt

Temperature, 67 F; Rel. Humidity, 12 percent

W_{NTO}, 1.5 lb; W_{HZ}, 1.3 lb

TABLE 1
(Continued)

Test No. 62 (continued)

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
0.118	0.500	0.286
0.322	0.910	0.381
0.410	1.273	0.857
0.433	1.910	1.571
0.455	1.910	1.619

Test No. 63 - Nitrogen Tetroxide Lead on Dirt
Temperature, 67 F; Rel. Humidity, 12 percent
W_{NTO}, 2.0 lb; W_{HZ}, 1.0 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
0.0975	0.318	0.095
0.436	1.091	0.524
0.465	1.363	0.666
0.533	1.728	1.238
0.669	1.091	0.476
0.720	1.091	0.476
0.825	0.728	0.286

Test No. 64 - Simultaneous Spill on Water
Temperature, 67 F; Rel. Humidity, 12 percent
W_{NTO}, 1.5 lb; W_{HZ}, 1.0 lb

TABLE 1
(Continued)

Test No. 64 (continued)

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
0.052	1.363	0.762
0.108	0.910	0.381
0.326	1.272	0.666
0.382	1.819	1.285
0.419	0.819	0.286

Test No. 65 - Hydrazine Lead on Water

Temperature, 67 F; Rel. Humidity, 12 percent

W_{NTO}, 1.5 lb; W_{HZ}, 1.3 lb

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
0.049	1.137	0.950
0.297	1.046	0.476
0.332	0.364	0.190
0.363	0.636	0.190
0.395	1.046	0.428
0.415	0.773	0.333
0.485	1.228	0.619

Test No. 66 - Nitrogen Tetroxide Lead on Water

Temperature, 67 F; Rel. Humidity, 12 percent

W_{NTO}, 4.0 lb; W_{HZ}, 2.0 lb

TABLE 1
(Continued)

Test No. 66 (continued)

Time, sec	Overpressure, psi	
	Station M-1	Station M-2
0.046	1.046	0.428
0.825	0.955	0.381
0.902	0.546	0.190
0.969	0.854	0.381

Hydrazine and Pentaborane

Test No. 67 - Simultaneous Spill on Dry Concrete
Temperature, 70 F; Rel. Humidity, 9 percent
W_{HZ}, 1.0 lb; W_{PB}, 0.7 lb
Trace Overpressure at Ignition

Test No. 68 - Pentaborane Lead on Dry Concrete
Temperature, 70 F; Rel. Humidity, 9 percent
W_{HZ}, 1.0 lb; W_{PB}, 0.9 lb
Trace Overpressure at Ignition

Test No. 69 - Hydrazine Lead on Dry Concrete
Temperature, 70 F; Rel. Humidity, 9 percent
W_{HZ}, 1.3 lb; W_{PB}, 0.7 lb
Overpressure of 2.635 psi (Station M-1) and 2.155 psi (Station M-2) after 2.011 seconds

TABLE 1

(Continued)

Test No. 70 - Simultaneous Spill on Asphalt

Temperature, 70 F; Rel. Humidity, 9 percent

W_{HZ} - 1.0 lb; W_{PB}, 0.7 lb

Overpressures of 2.365 psi (Station M-1) and 2.423 psi (Station M-2) after 0.00625 seconds

Test No. 71 - Pentaborane Lead on Asphalt

Temperature, 70 F; Rel. Humidity, 9 percent

W_{HZ}, 1.0 lb; W_{PB}, 0.9 lb

Overpressures of 2.455 psi (Station M-1) and 2.463 psi (Station M-2) after 0.01250 seconds

Test No. 72 - Simultaneous Spill on Dirt

Temperature, 70 F; Rel. Humidity, 9 percent

W_{HZ}, 1.0 lb; W_{PB}, 0.7 lb

Overpressures of 2.365 psi (Station M-1) and 2.230 psi (Station M-2) after 0.21025 seconds

Test No. 73 - Pentaborane Lead on Dirt

Temperature, 70 F; Rel. Humidity, 9 percent

W_{HZ}, 1.0 lb; W_{PB}, 0.9 lb

Overpressures of 2.500 psi (Station M-1) and 2.650 psi (Station M-2) after 0.01050 seconds

NOTES:

1. Total weight values are approximate quantities of propellant spilled during a test.
2. Time is taken from the point of first photocell signal generation; "t" notations signify photocell failure.
3. Time recorded is taken for the observation at Station M-1; shocks were detected at Station M-2 approximately 4.5 milliseconds later.

Additional Single Spills. Additional single spills of chlorine trifluoride, on various surfaces, were made during tests of this oxidizer with hydrazine and nitrogen tetroxide. A spill on dry concrete resulted in rapid evaporation of the liquid and no damage to the concrete surface. However, the propellant appeared to erode further cracks that were already present in the surface. Dirt and painted steel reacted to some extent with chlorine trifluoride; reaction was evidenced by sparks and weak audible reports. Spills into water generated several weak overpressure shocks with amplitudes as high as 0.037 psi at M-1, and 0.023 psi at M-2. Wood was ignited immediately upon contact.

Single spills of pentaborane were made on concrete, dirt, asphalt, and water at an ambient temperature of 70 F and 9-percent relative humidity. The fuel floated on the surface of the water for several seconds; it was ignited with a brief chlorine trifluoride purge and burned on the water until exhausted. After delays of a few seconds, ignition occurred on the other surfaces with weak audible reports.

Pentaborane spilled on dry concrete at 64 F and 10-percent relative humidity failed to ignite; evaporation was complete in several seconds. Dirt and asphalt caused ignition of the propellant, after slight delays, under the same ambient conditions. In the latter cases, there was some question of surface contamination as hydrazine had been burned on the same surfaces some time prior to the pentaborane tests.

Results of instrumented single spills are summarized in Table 2.

CONCLUSIONS

Information from these Small-Scale Hazard Classification Tests will be integrated with the data generated from the other phases of the Hazard Classification of New Liquid Propellants Program to define safety criteria for handling and bulk storage.

The following conclusions regarding propellant reaction characteristics can be drawn directly from the results of the small-scale spills.

1. All propellant combinations tested, except nitrogen tetroxide/chlorine trifluoride, will result in ignition and fire in contact with each other.
2. All propellant combinations tested, except nitrogen tetroxide/chlorine trifluoride, result in reactions which may create overpressure shocks.
3. All tested combinations with recorded overpressures have TNT equivalents less than those resulting from liquid oxygen/RP-1 spills. It can be assumed also, from relative audible reports, that TNT equivalents for nitrogen tetroxide/pentaborane spills will be less than those from liquid oxygen/RP-1.
4. All igniting combinations, except hydrazine/pentaborane, yielded a series of low-amplitude shock waves.

TABLE 2

RESULTS OF INSTRUMENTED SINGLE SPILLS OF CHLORINE TRIFLUORIDE AND PENTABORANE

Test	Propellant	Surface	Temp., F	Relative Humidity, percent	Results
19	Chlorine Trifluoride	Dry concrete	62	13	Rapid boiloff of liquid, no reaction with or damage to the concrete surface
20	Chlorine Trifluoride	Dirt	60	14	Slight reaction with small sparks and "pops"
21	Chlorine Trifluoride	Water	59	15	Several small overpressures, reaching 0.037 psi on M-1 and 0.023 psi on M-2, were recorded
22	Chlorine Trifluoride	Asphalt	57	16	Vigorous burning and rapid deterioration of surface
23	Chlorine Trifluoride	Painted steel	56	16	Same as 20
24	Chlorine Trifluoride	Wood	56	16	Smooth and rapid burning of surface
25	Pentaborane	Dry concrete	70	9	Ignited with small "pop" on surface after delay of a few seconds
26	Pentaborane	Dirt	70	9	Same as 25
27	Pentaborane	Asphalt	70	9	Same as 25

TABLE 2

(Continued)

Test	Propellant	Surface	Temp., F	Relative Humidity, percent	Results
28	Pentaborane	Water	70	9	Floated on top of water without ignition; however, it burned on top of the water after ignited with chlorine trifluoride
29	Pentaborane	Dry concrete	64	10	No ignition; finally evaporated
30	Pentaborane	Dirt	64	10	Ignited after slight delay; however, residual hydrazine might have been on surface
31	Pentaborane	Asphalt	64	10	Same as 30

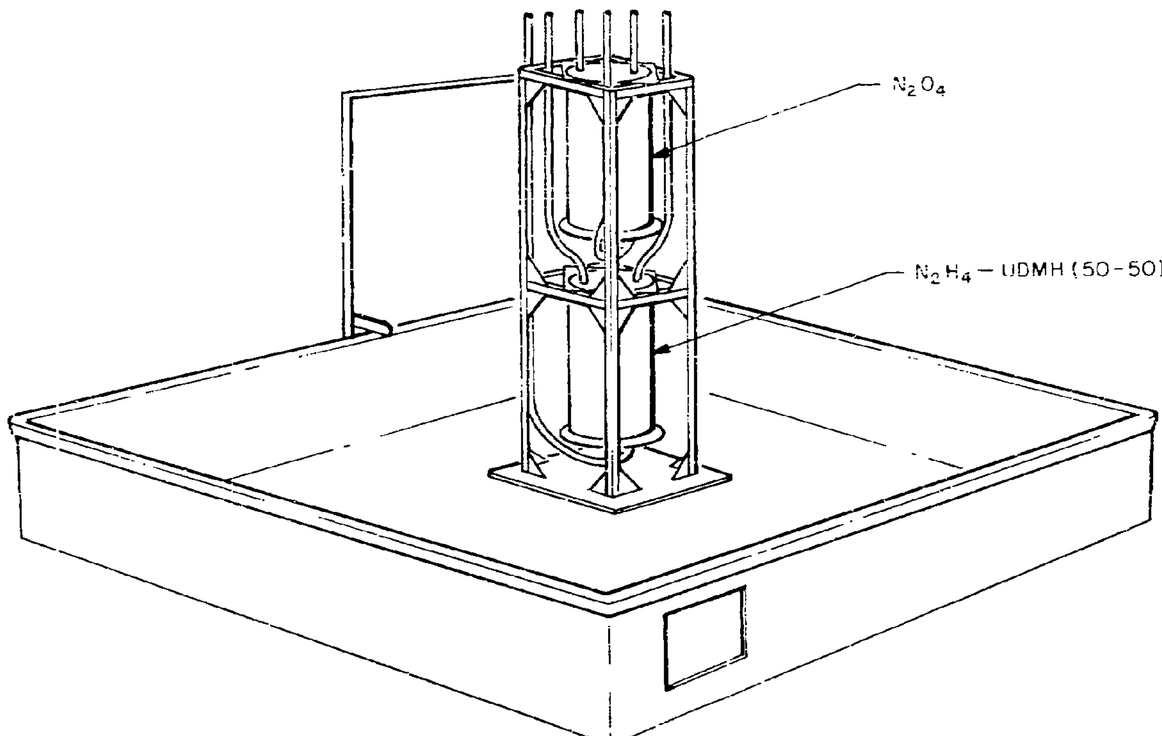
5. All hydrazine-base fuels that ignite will yield vapor-phase detonations between the fuel and air until complete surface burning begins.

6. Pentaborane spills may generate hydrogen which will detonate with air.

7. If possible, spills of pentaborane should be immediately ignited to prevent formation of toxic vapors and eliminate fortuitous ignition.

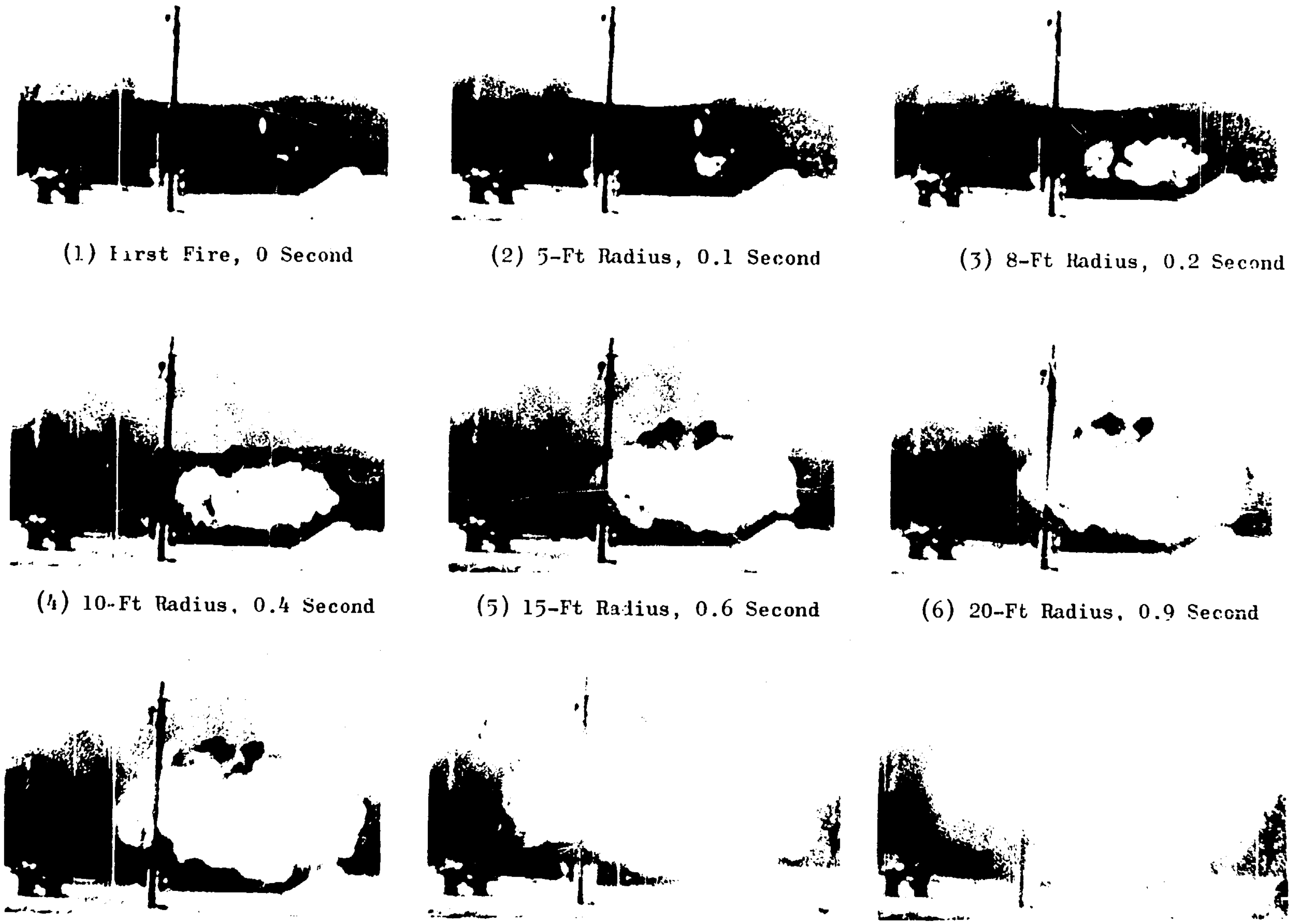
Supplement 3: Titan II Propellant Hazards

Several inquiries have been made concerning the characterisitcs of formation of the ball of fire (fireball) on the spill reactions aboveground in the tray. This information was not included in the Titan II Propellant Hazards Special Final Report, where the emphasis was placed on blast and fire phenomena that occurred in the silo and underground tunnels. Figure 20 shows the test configuration used on the above-ground spills in the tray. The oxidizer (200 lb of nitrogen tetroxide) and the fuel (100 lb of (50-50) hydrazine-UDMH) were spilled from tanks that were placed in a test-stand structure with the oxidizer tank positioned above the fuel. Blast measurements and photographic coverage were taken. The spills, identified as test 11 and test 8, had slightly different spill conditions. Test 11 was a simultaneous rupture of the two propellant tanks while test 8 was an oxidizer lead. The oxidizer tank was ruptured 2 seconds before the fuel tank on test 8. On test 11, the ball of fire reached a maximum radius of approximately 32 feet within 1.5 seconds after rupture. On test 8, a maximum radius of 32 feet was reached 1.85 seconds after the first noticeable ignition. Figure 21 shows the film sequences of the growth of the fireball resulting from the propellant reaction on test 8.



TRAY DIMENSIONS	
SIDES	20FT x 20FT
DEPTH	2 FT

Figure 26. 1/10-Scale Test Apparatus in Position for Above-Ground Spill



(1) First Fire, 0 Second

(2) 5-Ft Radius, 0.1 Second

(3) 8-Ft Radius, 0.2 Second

(4) 10-Ft Radius, 0.4 Second

(5) 15-Ft Radius, 0.6 Second

(6) 20-Ft Radius, 0.9 Second

(7) 22-Ft Radius, 1.2 Seconds

(8) 25-Ft Radius, 1.4 Seconds

(9) 30-Ft Radius, 1.6 Seconds

Figure 21. Ball-of-Fire Growth Rate, Test 8

The ball-of-fire growth rates (Table 3) for each test, are estimated data which were obtained from inspection of the motion picture frame sequences. The radius of the fireball was estimated by comparing its size to the 20 ft x 20 ft spill tray.

As shown in Table 3, the fireball from the oxidizer-lead spill was more rapid in growth during the initial hypergolic reaction than the simultaneous spill.

After this initial growth, the fireball remained unchanged on both test 11 and 8 for approximately 0.2 seconds. Further increase to maximum size was noticeably affected by overpressure pulsations that occurred within the ball of fire. These overpressures were recorded by the blast instrumentation. Comparison of the final phase of formation of the ball of fire shows the growth to be more rapid on the simultaneous spill than on the oxidizer-lead spill. Apparently the growth of the fireball was accelerated by the higher overpressures that resulted on the simultaneous spill. Figure 22 shows the overpressure traces recorded on both test 11 and 8.

It can be seen that at the 25-ft-microphone position, the overpressure for the simultaneous spill reached a maximum of 1 psi as compared to 0.5 psi for the oxidizer-lead spill.

<u>Conclusions</u>. From inspection of the high-speed film on the two aboveground spills (test 11 and test 8) three stages are apparent in the formation of the ball of fire resulting from the reaction of the Titan II propellants. These stages are:

1. The initial hypergolic reaction of the propellants which results in the most rapid expansion of the fireball,

TABLE 3

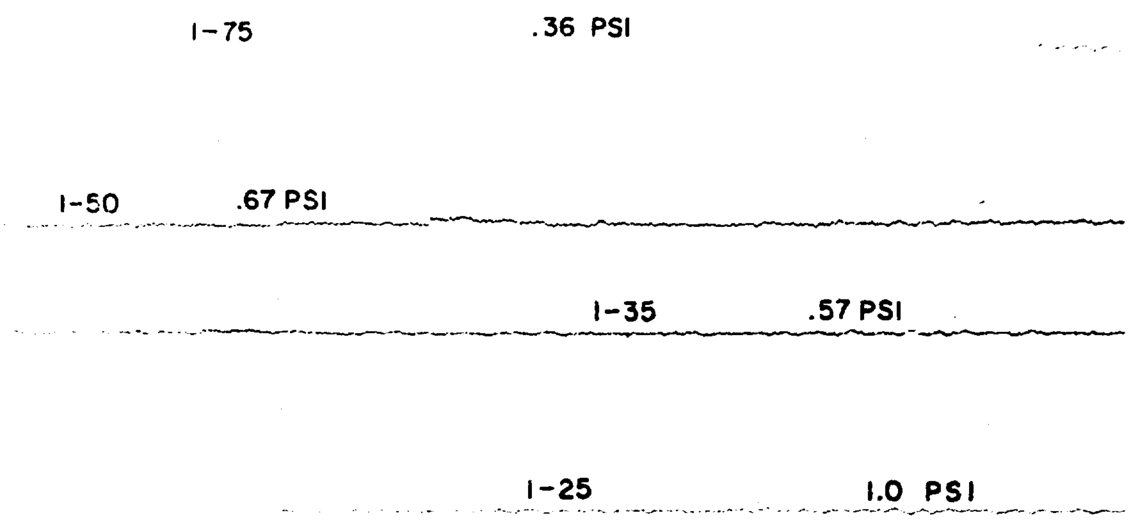
BALL-OF-FIRE GROWTH RATES

Test 11 Simultaneous Rupture			Test 8 2-Second Oxidizer Lead		
Time, sec	Ball-of-Fire Radius, ft	Remarks	Time, sec	Ball-of-Fire Radius, ft	Remarks
0	...	Rupture	0	0.5	Fire first noticeable
0.25	1.5		0.01	2.0	
0.275	2.5		0.05	3.0	
0.3	3.5		0.1	5.0	
0.325	4.0		0.15	6.0	
0.35	4.0		0.2	8.0	
0.375	4.0		0.25	10.0	
0.4	4.0		0.3	10.0	
0.425	4.0		0.35	10.0	
0.45	4.0		0.40	10.0	
0.475	4.0		0.45	10.0	First noticeable
0.5	4.0	First noticeable	0.5	15.0	overpressure pulse
0.625	6.0	overpressure pulse	0.55	15.0	

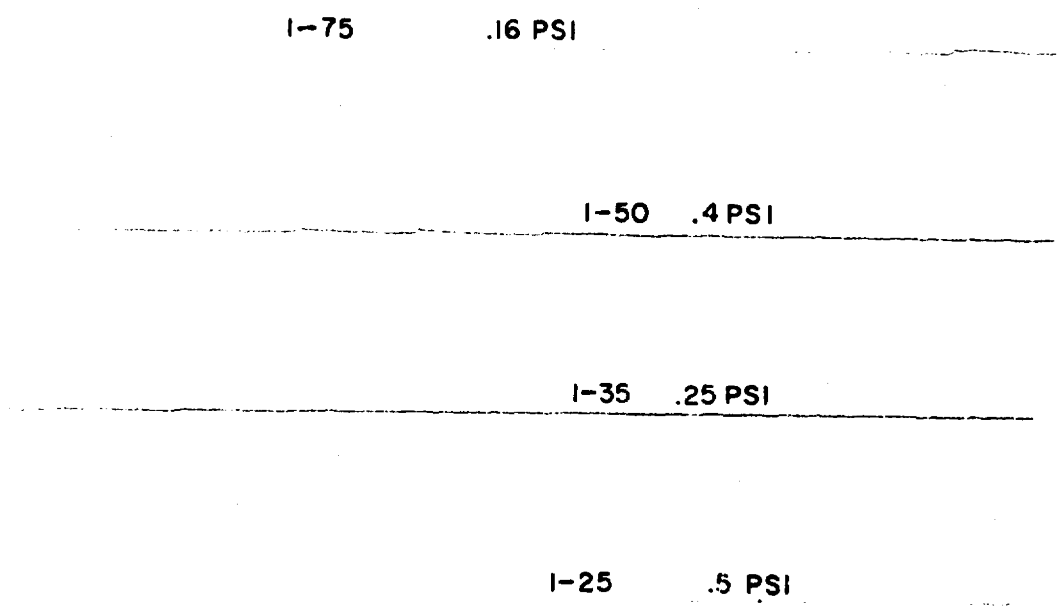
TABLE 3

(Continued)

Test 11 Simultaneous Rupture			Test 8 2-Second Oxidizer Lead		
Time, sec	Ball-of-Fire Radius, ft	Remarks	Time, sec	Ball-of-Fire Radius, ft	Remarks
0.75	10.0		0.75	17.5	
0.875	15.0		0.85	20.0	
1.0	20.0		0.95	22.5	
1.12	22.0		1.25	25.0	
1.25	25.0		1.5	25.0	
1.375	30.0		1.6	30.0	
1.5	32.0		1.85	32.0	Ball of fire starts rising
2.0	32.0	Ball of fire starts rising			



Test 11. Simultaneous Spill of 200 lb of Nitrogen Tetroxide and 100 lb of UDMH-Hydrazine (50-50) in Spill Tray



Test 8. Blast Pressure Measurements from Spill of 200 lb of Nitrogen Tetroxide and 100 lb of UDMH-Hydrazine (50-50) in Spill Tray, NTO led fuel by 2 Seconds

Figure 22. Oscillograms of Overpressures Generated on the Reactions Aboveground in Spill Tray

2. A period without apparent growth, the duration of which depends upon the time required for vaporized hydrazine to combine with air to form explosive vapor-phase mixtures, and

3. After ignition of these explosive fuel-air mixtures, the over-pressures generated cause expansion of the ball of fire to its maximum size. This last stage in the growth ends as the fireball begins to lift and dissipate.

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